COMMERCIAL HIGH CURRENT IGNITRON DEVELOPMENT

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ABSTRACT

Our overall goal is to develop and qualify devices capable of repetitively switching high peak currents (>1 MA) and large quantities of charge (>500 C). In 1988 we designed and tested a hollow-anode ignitron at levels of up 925 kA and 280 C per shot[1]. This level is three times that previously achieved with standard, commercially available tubes[2]. Our latest designs, developed with the cooperation of industry, incorporate a hollow anode into an industrial ignitron. Prototypes have recently achieved levels of 770 kA and 270 C per shot.

INTRODUCTION

The requirements imposed by rapidly evolving, advanced technologies have greatly surpassed the capabilities of present-day repetitive switching devices. Mass drivers and advanced laser inertial confinement fusion (ICF) systems now require energies of up to 100 MJ, while the requirements of some systems, such as the proposed Athena laser will approach 1 GJ. To keep the size of such systems within reasonable bounds, small capacitor packages of high energy density (50 kJ normalized to the volume of a SCYLLAC package, with prototypes exhibiting densities to 250 kJ) and peak current capabilities of 750 kA per capacitor have been developed. However, development of switches capable of transferring high currents and large amounts of charge has not progressed with equal vigor, and the switching technology of the early 1960s cannot adequately meet the needs of present day systems. Without doubt, the size and cost of switches impose increasingly severe limitations on new systems. A switch capable of simultaneously conducting 1 MA and 1000 C per shot will satisfy these needs.

The proposed Athena laser, which this work supports, points up the limitations that present-day technology places on system size. Studies show that cost effectiveness and reliability depend heavily on the availability of suitable switches. The switching system in the present Nova laser facility uses 125 sets of paired ignitrons connected in series (250 total) for voltage holdoff. Each set nominally switches a peak current of 100 kA and 50 C per shot. Athena would require 1250 sets of ignitrons (2500) at the present level of technology. A tenfold increase in auxiliary systems (for example, monitors, triggering, and heat management) would also be required. However, a system built from 125 switches capable of handling 1 MA each could use the present Nova support systems with no increase in size.

A collaborative development effort is now under way between LLNL, the manufacturers [Richardson Electronics and English Electric Valve (EEV)], and Texas Tech University to design and manufacture ignitrons with the required capabilities.

DEVELOPMENT HISTORY

Our first "Hollow Anode" (HA) tube, Fig. 1, was constructed in a demountable configuration to allow it to be used as a test bed for developing and testing new concepts. The key features of this tube are; a stainless-steel hollow-anode, axial ignitor, and close spacing of the anode-cathode gap. The limitations of conventional ignitron designs at high currents and charge transfers: ignitor resistance collapse, high tube drop, and an unstable discharge, are minimized by this design.

Our tests of the "demountable-hollow-anode" ignitron (DM-HA) are now complete. The DM-HA ignitron with a 6-mm anode-to-cathode spacing has transferred 950 kA and 260 C per shot, with a tube drop of 120 V. The tube is stable at the 6-mm spacing with some instability appearing as the anode-to-cathode gap is widened. The tube drop as a function of current is plotted in Fig. 2 for spacings of 6, 12, and 25 mm. The 6- and 12-mm data have been previously published. The slope of the 6- and 12-mm curves is 90-$\mu\Omega$, half of which can be accounted for by resistive drop in the tube structure. For the 12- and 25-mm spacings, instabilities in the discharge begin to appear at the lower currents as fluctuations in the tube drop, but disappear as the current is increased. Even at 950 kA, the voltage drop for the HA configuration is one-third of a experimental, solid-anode commercial tube at 500 kA (NL-8205/X101),

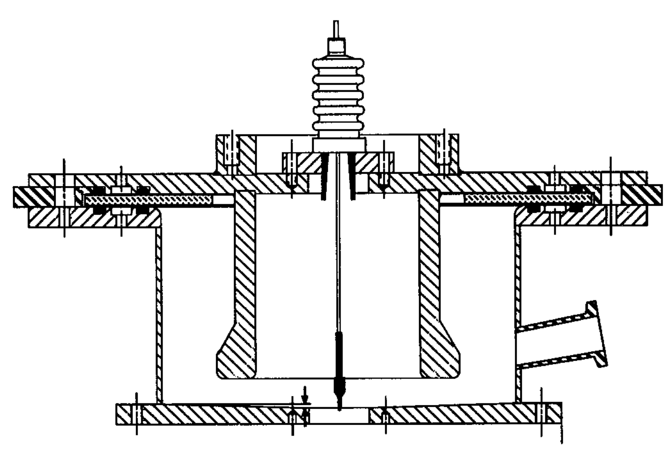

Fig.1 Cross-section of the "De-Mountable Hollow-Anode" ignitron.(DM-HA)

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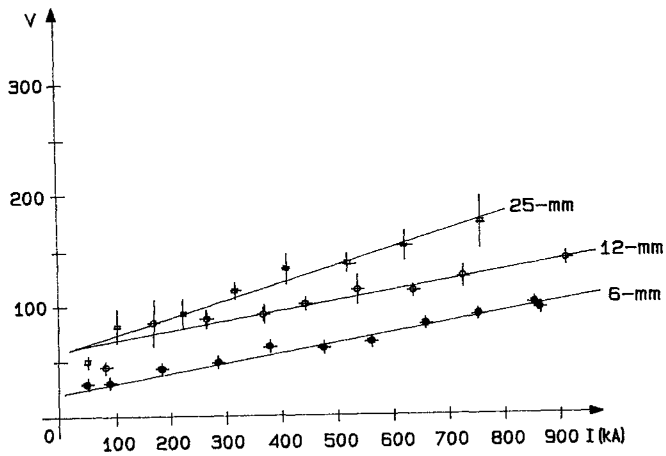

Fig. 2-Tube drop as a function of current for the DM-HA tube, at 6,12, and 25 mm A-K spacings. Bars through points represent scatter of data.

and one-tenth of the unmodified tube (GL-8205)[3]. Plots of ignitor resistance as a function of current show virtually no change, whereas most tubes have exhibited a resistance collapse at levels of 300 to 500 kA. Once the resistance has fallen to <0.2 Ω we cannot fire the tube.

Richardson Electronics has produced a commercially packaged, graphite-anode HA tube designated the NL-9000, Fig. 3, using data from the demountable HA tube and a conceptual design for a sealed tube based on the HA geometry. The major differences between this tube and a conventional ignition, as it is in the DM-HA tube, are a hollow anode, axial ignitor, and the close spacing of the anode to the mercury. The approximation to the DM-HA is good considering

Fig 3-NL-9000 Ignitron.

manufacturing constraints and available tooling, which dictated the manner of implementation. The anode had to be made thicker to make it stronger, as it was made from graphite, rather than stainless-steel, and the anode-to-cathode spacing was changed from 6-mm to the less optimal 12-mm, to allow for manufacturing tolerances. The ignitors were installed axially, but in the normal manner through the bottom, rather than through the anode. The standard ignitron seal was used on the neck, although it was shortened to increase strength. Schematic cross-sections of the NL-9000 and standard ignitron tube are compared in Fig 4.

The anodes of the NL-9000 are made from graphite, since it is readily available, and cost effective. Other versions of this tube using more exotic materials, such as vacuum cast stainless-steel or molybdenum, will be prototyped, but are substantially more expensive to produce.

TEST PROCEDURES

A large capacitor bank originally rated at 50 mF and 5 kV, supplies current for testing. The attrition of capacitors, and the desire to prevent further losses has since reduced these ratings to 45 mF and 4.5 kV. The discharge waveform is a damped sinusoid of 5-7% reversal, tuned to match the Nova bank parameters (~150 µs to peak).

"Synthetic" testing has been recently incorporated into the test stand to simulate operation at voltages up to 10 kV. Synthetic testing utilizes two banks, a small, high-voltage bank, and a large, lower voltage, but high-current bank. The high-voltage bank is connected directly to the tube, and tests recovery and hold-off. The high-current bank is isolated through a series switch, composed of eight size "D" ignitrons, connected in parallel. Both banks are discharged simultaneously through the tube, and together simulate a single, large, high-voltage bank. The synthetic test circuit uses a single 14.5 µF capacitor, in series with a 13.5 µH inductor, in a critically damped RLC circuit. The tube is mounted in a carefully centered and leveled coaxial structure to balance magnetic forces and to maintain a constant mercury-anode spacing.

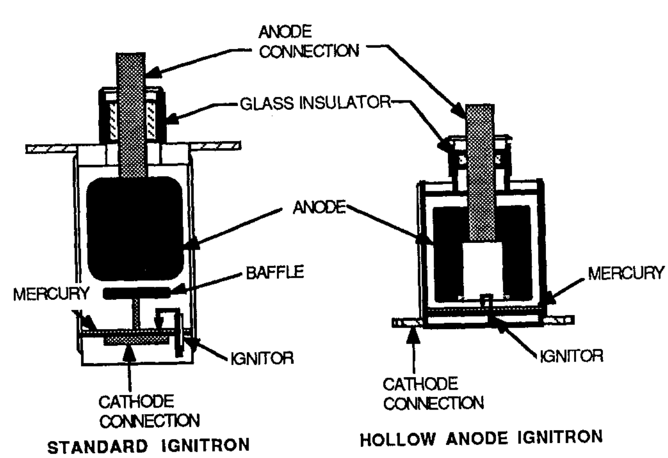

Fig. 4- Schematic diagrams of standard ignitron and hollow anode ignitron compared.

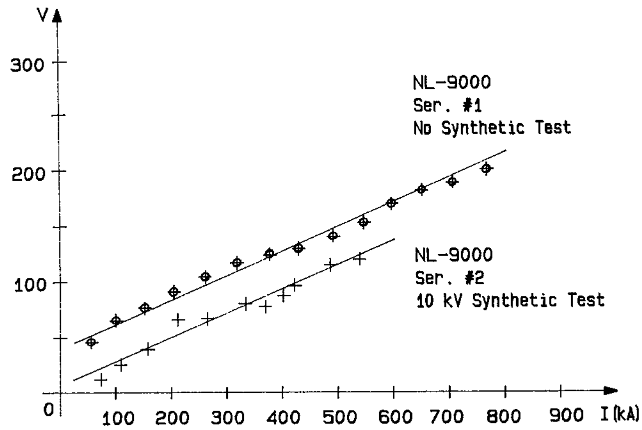

Fig. 5.-Tube drop curves for NL-9000 Ser. #1 and #2. Tube #1, no synthetic test; tube #2, synthetic test voltage, 10 kV. All plotted points are multiple datum.

We characterize previously untested tube types by measuring the tube drop as a function of current. The peak current is raised in 50-kA increments every 10 shots, beginning at 50 kA until tube failure occurs or the bank limits are reached. The initial life test levels are then started at 66% of the peak current at failure or the bank limit, whichever comes first. All new tubes of the same type tested after this are started at 50 kA and stepped to the test level in a like manner.

Rogowski coils are used to take current measurements, and the voltage drop across the tube is measured differentially at the current peak, when the output of the Rogowski coil (di/dt) passes through zero. The output of the Rogowski coil is numerically integrated twice with a Tektronics 7854 oscilloscope to measure charge transfer. The particular capacitors used in our bank store charge non-linearly with voltage, so the measured charge transfer always exceeds Q=CV by a small amount.

RESULTS

The first NL-9000, Ser. #1, was tested without synthetic test, to the maximum level attainable in the present circuit configuration, 770 kA and 270 C per shot. At 770 kA the tube took 3-4 minutes to recover to the bank voltage (4.5 kV). The higher bulk resistivity of graphite (800 μΩ-cm) as compared with stainless-steel (72 μΩ-cm) is believed to cause the higher slope (220 μΩ) of the tube drop curve in Fig. 5, compared to the DM-HA curves. At the higher current levels some ignitor resistance loss was noticeable, but the high level of retained resistance (250 Ω) at the 770 kA operating level is remarkable.

Both ignitors of this tube shorted after a prefire, which followed after eight 770 kA shots. The estimated fault current was ~500 kA. The ignitor resistances measured just before the prefire were both about 250 ohms. Several prefires had occurred previously to this at estimated levels up to ~700 kA without damage. The nature of this prefire was unlike those that came before it, as it was distinguished by an asymmetric current flow in the mountings which displaced the connections to the tube. We concluded from this that the breakdown had occurred off of the tube axis.

A postmortem conducted at Richardson Electronics found that the tips of both ignitors had been snapped off, and that the ignitor feedthroughs were cracked. The fracture patterns of the feedthroughs were identically aligned, indicating that the ignitors were destroyed by either by mercury jetting or shock waves in the mercury generated by the prefire.

The ignitor circuits of all tubes tested after this were modified to protect the tube. An anode fall coupling circuit was connected to the second ignitor, which couples the anode fall through a 20 nF capacitor, and an inversion transformer. If the tube should prefire, this circuit is intended to trigger the tube and force a transfer to a normal discharge mode. A 5-Ω non-inductive resistor was also placed in series with each ignitor to limit the current flow through the ignitor if an arc attachment should occur. We do not know if these changes effectively protect the tube.

The boundary of the anode and the anode bolt was also damaged. Arcing between the bolt and the anode had begun to burn away the interface, which would eventually have caused the anode to break loose. NL-9000, Ser. #3, was inspected radiographically and showed no signs of deterioration after 210 shots at 500 kA and 200 C per shot. This would set an upper limit for the interface between 500 and 770 kA.

A second NL-9000, Ser. #2, was installed, and tested in the normal manner. The synthetic test circuit was installed for this test, and set to 10 kV, and a recharge period of 35 seconds. The tube recovered after every shot at a rep-rate of 1 pulse per minute, up to the life test level of 500 kA. After two shots at 500 kA, a broken weld caused the tube to go to air.

The synthetic test circuit noticeably and unexpectedly improved the operation of the NL-9000. The plots of voltage drop vs. current, Fig. 5, for the first two tubes were identical in slope but the synthetic test circuit displaced the curve downward by 20-30 V. The tube drop and di/dt traces were substantially smoother under synthetic test. At lower currents where the discharge is unstable, the synthetic test circuit partially stabilizes the discharge. The same tests were repeated on NL-9000, Ser. #3, with the synthetic test voltage set at 0, 10 kV, and equal to the main bank voltage, to eliminate tube variation and voltage effects. The results confirmed that the synthetic test circuit changes the operating characteristics of the tube. The synthetic test circuit lowers anode dissipation by 20% at the 500 kA current level, but this is expected to have a only moderate effect on the the lifetest data.

We believe the effect of the synthetic test circuit can be attributed to the accelerated development of the discharge, as previously described by Cummings[4]. Whereby, a small number of arc spots form about the ignitor after ignition, and spread rapidly across the mercury cathode with rising anode current. The shorter time constant of the synthetic test circuit is believed to bring this process to completion in advance of the main bank discharge, thereby increasing the efficiency of the discharge.

The NL-9000, Ser. #3, was used for the 500 kA lifetest. As in previous tubes, it was stepped to 500

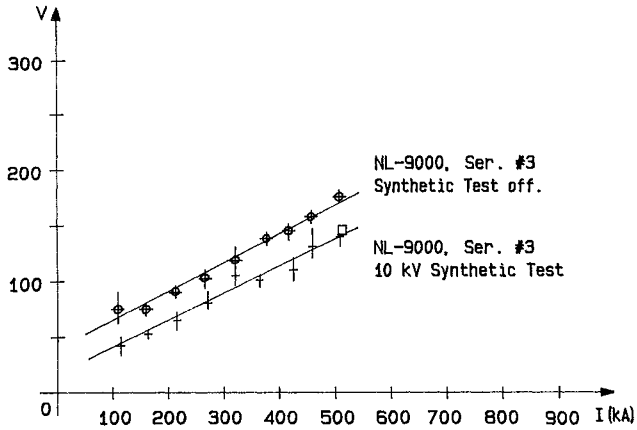

Fig. 6-Tube drop curves, NL-9000 Ser. #3, with and without synthetic test. Bars through points represent scatter. Shaded bar represents 2-sigma variation of drop over the lifetest.

kA in 50 kA steps. The tube drop data were taken both with and without synthetic test. Both curves are plotted in Fig. 6. Data points exhibit some scatter as this tube was not as stable as the previously tested tubes. The 2-σ deviation of the drop over the lifetest is superimposed over this.

The lifetest was run with the synthetic test circuit set to 10 kV, and a recharge time of 35 seconds. The repetition-rate was limited to approximately 1 pulse per minute by the recharge rate of the main bank. The tube was operated at this rate, in runs of 20-50 shots, at a level of 500 kA, and 200 C per shot, for a total of 590 shots to date. The anode header temperature after a 50 shot run was 112°C. Two prefires occurred during the lifetest, which we attributed to the lack of anode preheating, since they occurred immediately after a cold start. The ignitor resistances of this tube started at 332 and 425 ohms respectively, and decreased to almost half of their initial values by shot #290 of the lifetest, where the resistances were 170 and 229 ohms. The decrease continued at a much slower rate, falling to 159 and 210 ohms at shot #530. Extrapolating the to less than 1 ohm of ignitor resistance, would imply a tube life of about 3,000 shots.

Test data for all three tubes are summarized in Table 1.

CONCLUSIONS

The hollow anode ignitron design has been successfully transferred to a commercial ignitron package, with a minimal alteration of existing designs. Graphite anodes have been shown usable to currents of at least 500 kA, and voltages to 10 kV. Deterioration of the anode-stud interface seen at 770 kA, may be avoidable by increasing the contact area. Operation at higher currents and efficiencies will require the use of metal anodes to lower the resistive drop, which in a graphite HA tube, exceeds the arc drop.

Our implementation of the synthetic testing technique changes the operating characteristics of the tube, and may generate life testing results that are slightly better than a tube operated in the normal manner. This technique may have an application where the highest possible switch efficiency is required.

Table 1. Summary of Results

Ignitron NL-9000	Max Test Voltage Bank/Syn. (kV)	Max. Test Current (kA)	Ignitor Resistance (Start) (Ohms)	Ignitor Resistance (Finish) (Ohms)	# Shots Lifetest, (500 KA &) (200 C/shot)	# Shots (Total)	Tube Status
Ser. #1	4.5/0	770	464/687	See text	N/A	136	Failure
Ser. #2	3.35/10	533	N/A	N/A	N/A	79	Failure
Ser. #3	3.4/10	525	332/425	159/210	590	890	Operating

REFERENCES

[1] D.B. Cummings, R. Kihara, and K.S. Leighton, "High Current Ignitron Development," presented at the 18th Power Modulator Symposium, Hilton Head Island, South Carolina, June 20-22, 1988.

[2] R. Kihara, "Evaluation of Commercially Available Ignitrons as High-Current, High-coulomb Transfer Switches," presented at the IEEE 6th Pulse Power Conference, Arlington, Virginia, June 29-July 1, 1987.

[3] R. Kihara, "Test Results: GL-8205 and NL-8205/X101 Ignitrons," Internal report to NOVA power conditioning group, Lawrence Livermore National Laboratory, July 27, 1987.

[4] D.B. Cummings, "Ignitron Discharge Growth During High-Current Pulses", IEEE Transactions on Communications and Electronics, no. 58, Sept. 1963.